

Oscillations in the stable starless core Barnard 68

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ABSTRACT

New molecular line observations of the Bok globule Barnard 68 in HCO^+ irrefutably confirm the complex pattern of red and blue asymmetric line profiles seen across the face of the cloud in previous observations of CS. The new observations thus strengthen the previous interpretation that Barnard 68 is undergoing peculiar oscillations. Furthermore, the physical chemistry of B68 indicates that the object is much older than the sound crossing time and is therefore long-lived. A model is presented for the globule in which a modest external pressure perturbation is shown to lead to oscillations about a stable equilibrium configuration. Such oscillations may be present in other stable starless cores as manifested by a similar signature of inward and outward motions.

Key words: radiative transfer - ISM: globules - stars: formation - submillimetre

1 INTRODUCTION

One difficulty in identifying a potential site of future star formation has been to decide whether a dense portion of a molecular cloud is likely to proceed to collapse to form a star or else is just a transient or a long-lived density enhancement. Models of supersonically turbulent cold molecular clouds readily produce localised density enhancements in colliding gas streams (e.g. Klessen et al. 2000; Padoan & Nordlund. 2002; Ballesteros-Paredes et al. 2003). However, in the simulations, the clouds either quickly dissipate on a sound crossing time or, if their density and size are such that the cloud mass exceeds the local Jeans mass, they may collapse to form stars. However, observations that show that the internal structure of some clouds is consistent with self-gravitating equilibrium suggest that the alternative of long-lived clouds should not be excluded. Unbiased observations of large swathes of molecular cloud gas point to cloud survival timescales a few sound crossing times but less than order ten (Visser et al. 2002). Theoretical models of small clouds in equilibrium closely match the observations and suggest that small clouds may be categorized as either ‘stable starless cores’ or ‘unstable pre-stellar cores’ using the terminology suggested in Keto & Field (2005) (note that the terms ‘starless cores’, ‘pre-protostellar’ and ‘pre-collapse’ cores are commonly used in observational work). Such structures, in which local thermal pressure dominates over larger scale inertial forces, could represent the end point of the turbulent cascade in larger scale molecular clouds. Thus the picture of the interstellar medium as a purely turbulent phenomenon, and all clouds as purely transient may not be applicable on the scale of the smaller clouds such as Bok globules and starless cores (Fig 1). Since star formation in regions such as Taurus and Ophiuchus takes place in these small clouds, an understanding of whether equilibrium conditions can prevail is crucial in order to

be able to understand the initial conditions of star formation and the firm identification of infall candidates.

Barnard 68 (LDN 57, CB 82 hereafter B68, Figs 1 and 2) is an excellent test case of an object that could either be a stable starless core or unstable pre-stellar core. Because B68 is nearby (~ 125 pc) and fortuitously seen in silhouette against the galactic bulge, Alves et al (2001a) were able to directly measure the dust extinction in the core with unprecedented accuracy using deep near-infrared extinction measurements from H and K imaging of background stars. With the assumption of a uniform gas to dust ratio, the gas density profile for this core is thus very well constrained as a cloud in hydrostatic equilibrium confined by external pressure: a Bonner-Ebert Sphere (Bonner 1956; Ebert 1955) which is a solution of the Lane-Emden equation for a bounded isothermal pressure-balanced sphere. However, we argue below that B68 is not isothermal and is possibly not in hydrostatic pressure balance. The high quality of the absorption data and the precise determination of the column density removes a major source of uncertainty for investigating the internal structure of this possible prestellar core candidate.

The dust obscuration map in Fig 2 Alves et al. (2001b) show that B68 consists of an approximately spherical component of radius 12500 au with a markedly off-centre dust peak. There is also a lower density extension to the south-east. Alves et al. (2001a) estimated that the central density of B68 to be $\sim 2.5 \times 10^5 \text{ cm}^{-3}$ giving a total mass of the cloud of $\sim 2M_{\odot}$. Note that Hotzel et al. (2002) argue that B68 is substantially closer (~ 80 pc) than the 125 pc used by Alves et al. (2001a) which would make the cloud smaller and less massive.

The Alves et al. (2001a) paper has led to intense interest in B68 and its basic physical and chemical properties have now become well constrained. Several measurement of the gas and

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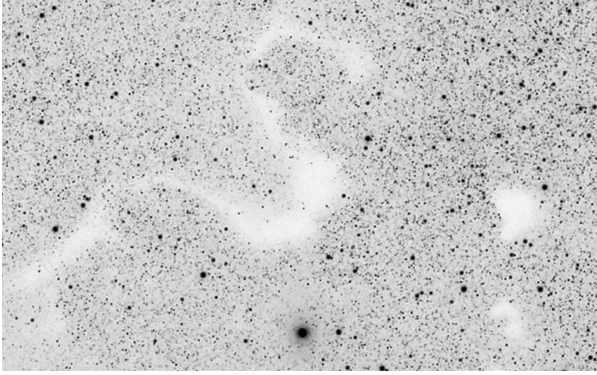


Figure 1. Barnard 68 (lower right) and nearby molecular clouds including Barnard 72, the snake nebula. Image credit and copyright Gary Stevens

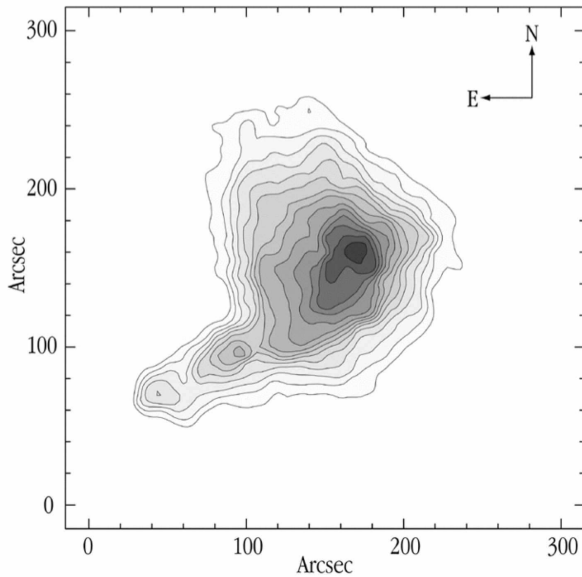


Figure 2. Iso-extinction map of B68 from Alves et al. (2001b). Image credit and copyright ESO

dust temperatures have been made. ISOPHOT observations by Langer & Willacy (2001) observations indicate a cold central dust temperature of 7K surrounded by a warmer envelope. Hotzel et al. (2002) use ammonia inversion lines to measure a gas kinetic temperature of 10 ± 1.2 K. Similarly, Lada et al. (2003) find a gas temperature of 10.5 K from ^{12}CO measurements in B68. These results are entirely consistent with continuum submillimetre observations and radiative transfer models of this and other sources of similar evolutionary age (Evans et al. 2001). These models clearly show that the cores possess significant temperature structure, with a warmer (~ 10 -15 K) envelope surrounding a colder (~ 5 -8 K) inner region.

The above temperatures are also consistent with molecular observations: The species used for calculating the gas temperature show evidence for heavy depletion due to freeze-out onto dust grains in the central regions of B68. Indeed, dust emissivity measurements by Bianchi et al. (2003) point to ice covered coagulated grains in the core of B68. The depleted species include H_2O , NH_3 , CO , CS and even N_2H^+ (Bergin et al. 2002; Bergin & Snell 2002; Hotzel et al. 2002; Di Francesco et al. 2002; Lai et al. 2003). For reasons that are still not clear, N_2H^+ is found to be remarkably re-

sistant to freeze-out and traces matter to surprisingly high densities in many cloud cores. The chemistry of N_2H^+ is relatively simple; it is formed by reaction of N_2 with H_3^+ and destroyed by dissociative recombination and reaction with CO . The main loss route for CO itself being reaction with H_3^+ . The high N_2H^+ abundances that are seen in many regions of moderate to high depletion has previously been ascribed to the low surface binding energies of N_2 and related species, but recent laboratory and theoretical work suggests that the binding energies are probably larger than previously thought. In any case, at very high densities and after long periods of time, even N_2H^+ will freeze-out. In B68 Bergin et al. (2002) estimate that N_2H^+ is depleted by a factor of 2 (between $A_V \sim 2 - 17$), whilst Di Francesco et al. (2002) suggest that the level of depletion may be an order of magnitude larger. The central density of B68 is not anomalously high, so the obvious conclusion is that the core has been quasi-static for an exceptionally long period of time.

The chemical determination that B68 has a long lifetime is important in understanding the evolution of the cloud because both stable and unstable Bonnor-Ebert spheres have an approximate balance of thermal and gravitation forces, provided the clouds are not in free fall (Keto & Field 2005). Therefore, observations of structure consistent with an approximate balance of forces is an ambiguous indicator of the evolutionary fate of a cloud.

The observations of starless cores such as B68 often show spectral line profiles indicating large scale gas motions. If interpreted in terms of simple contraction or expansion, the clouds could not have lifetimes longer than a crossing time. If a starless core can exhibit significant internal motions yet not ultimately collapse or evanesce, this would have profound implications for the continuing attempts to firmly identify infalling prestellar cores and test the competing dynamical models of star formation.

The spectral line observations of Lada et al. (2003) show profiles that are all double peaked and asymmetric but, most remarkably, they alternate between being red asymmetric and blue asymmetric across the core. These observations consist of $\text{CS } J = 2 - 1$ line profiles and a velocity centroid map of $\text{C}^{18}\text{O } J = 2 - 1$. In this paper we present additional molecular line observations of $\text{HCO}^+ J = 3 - 2$ in a two-dimensional pattern covering the face of B68. In sections 2 these profiles are presented and compared with the data of Lada et al (2002). Section 3 describes a dynamical model for this cloud to account for the shapes of the line profiles and conclusions are drawn in section 4.

2 OBSERVATIONS

JCMT observations of the $\text{HCO}^+ J = 3 - 2$ line were collected gradually in service observing mode over the year August 2003 to August 2004. In addition to observing across the east-west strip of points examined by Lada et al. (2003), data were also gathered from several other strips to build up a map of 38 separate pointings. The Lada et al. (2003) $\text{CS } J = 2 - 1$ data are reproduced in figure 3. Figure 4 shows the location of the JCMT pointing positions against the Alves et al. (2001a) image of B68. Good signal to noise at each point was preferred over additional pointings in order that the substructure of the line profile could be adequately detected. The data were reduced in the standard manner using the *SPEX* package in the *STARLINK* suite of astronomical software. A beam efficiency of 0.65 was used to convert the temperatures to the T_{mb} scale.

Figure 5 is a map of the $\text{HCO}^+ J = 3 - 2$ line profiles. Individual panels are separated by 10 arcseconds to the north and/or east. The central east-west profiles are at the same declination as

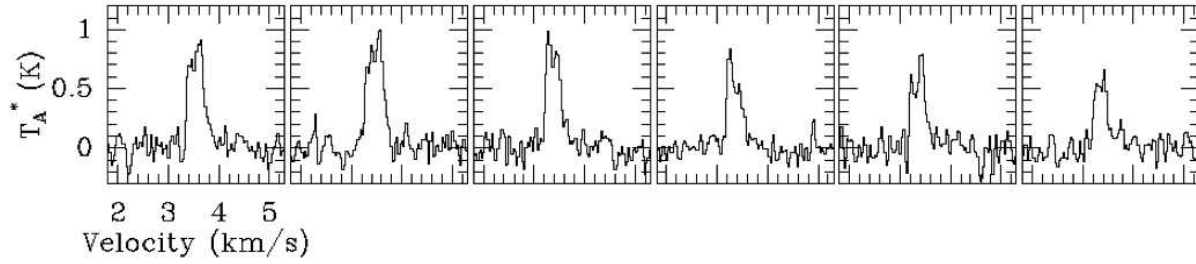


Figure 3. Lada et al (2003) line profiles of CS $J = 2 - 1$ across a strip through B68. The profiles are separated by 24 arcseconds.

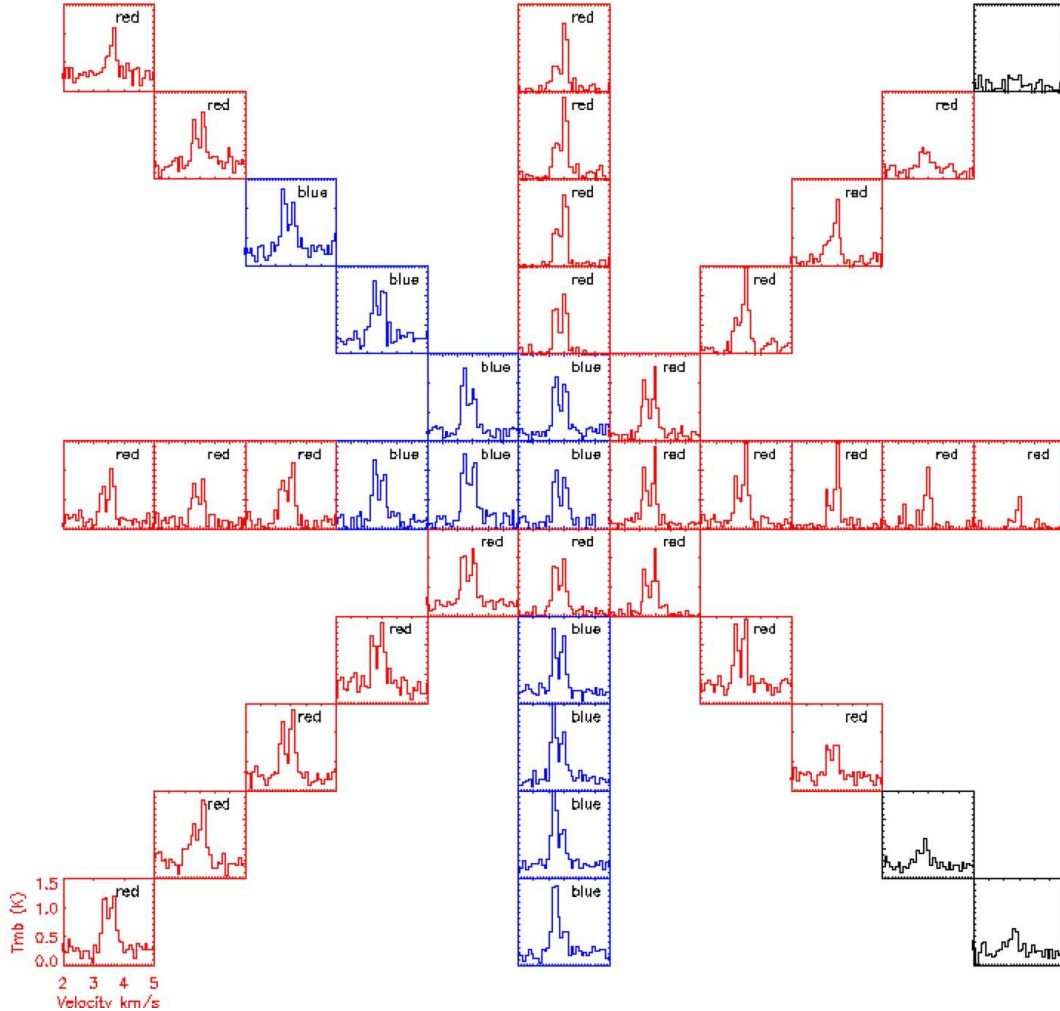


Figure 5. JCMT line profiles of HCO⁺ $J = 3 - 2$ across B68.

the Lada et al. (2003) profiles reproduced in Fig 3. Comparing the profiles it is immediately obvious that the pattern of asymmetry changes in the CS $J = 2 - 1$ line observed by Lada et al. (2003) is present in exactly the same way in the HCO⁺ $J = 3 - 2$ line. The rest of the data show that the distribution of the asymmetric profiles exhibits some overall order in that there are large contiguous blocks of red or blue asymmetric profiles. Lada et al. (2003) also used the difference of the centroid velocities between their C¹⁸O and CS $J = 2 - 1$ data to construct a map of the asymmetries across the face of B68. Again, the line profiles obtained here match this distribution of red and blue asymmetries closely. The fact that

species/transitions with different chemical behaviours and excitation characteristics apparently trace the same kinematics is indicative of bulk motions propagating deep into the core (but traced no deeper than the freeze-out radius: cf the N₂H⁺ data of Lada et al 2003, which exhibit somewhat different kinematics extending to the very centre of the core), rather than disturbances in the surface layers. In this context, it is interesting to note (see Figure 6) that the velocity of the self-absorption dips does not vary significantly across the source. This would again suggest that the origin of the kinematics and the reversal of the line profile asymmetry is due to dynamical activity extending deep into the cloud.

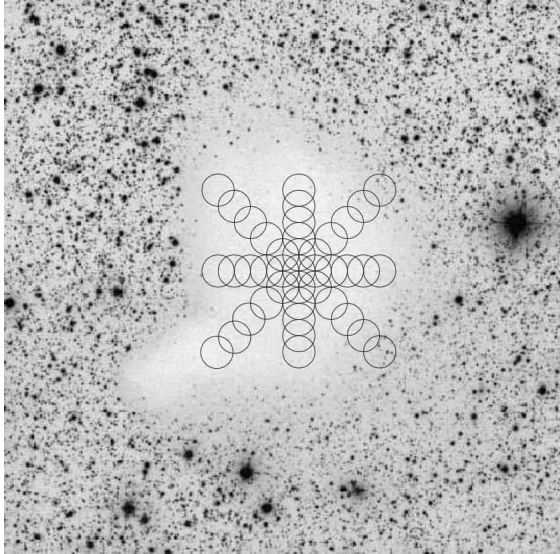


Figure 4. Pointing positions of JCMT shown projected against reverse greyscale ESO optical image of B68 (Alves et al 2001). The circles represent the 15'' beamsize of the JCMT.

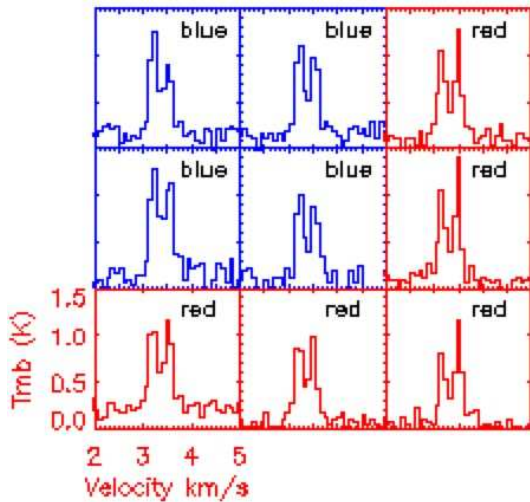


Figure 6. The central nine profiles of the JCMT data from the previous figure allowing detail of the asymmetry to be seen more clearly

3 DISCUSSION AND MODEL

The observed velocity pattern is very hard to explain with simple combinations of infall, outflow or rotation (or depletion). For an optically thick cloud undergoing collapse, blue asymmetric line profiles are expected everywhere. For a rotating cloud with no infall, an ordered set of red asymmetric and blue asymmetric profiles are obtained either side of the rotation axis (Redman et al. 2004). The red and blue asymmetric profiles cannot be caused by an outflow because there is no central source to power one present in B68. Because the pattern of asymmetry is present in two different tracer species then, as described above, it is likely an effect of gas motion i.e. a dynamical effect as opposed to an effect which varies by species such as line generation or depletion. So a new mechanism is required that could produce strong enough dynamical activity that the cloud can exhibit such readily observable asymmetric profiles.

Keto & Field (2005) analysed the hydrodynamical response

| Parameter | Adopted value or range |
|--------------------------------|---------------------------------|
| Outer radius | 0.09 pc (18500 au) |
| Central density | $2 \times 10^5 \text{ cm}^{-3}$ |
| HCO ⁺ abundance | 5.0×10^{-9} |
| Turbulent velocity | 0.15 km s^{-1} |
| Initial gas temperature range | 8 – 11 K |
| Initial dust temperature range | 13 – 16 K |

Table 1. Model parameters used. The temperature, density, and velocity fields which are determined from the numerical hydrodynamic code vary as a function of radius within the ranges listed in the table.

of Bonner-Ebert spheres to external pressure disturbances. They found that stable starless cores (i.e. those on the stable branch of the Bonner-Ebert sphere solution curve) can undergo bulk compression or expansion motions that do not tip the core into gravitational collapse, provided the amplitude of the perturbation is not too large. Such a model naturally explains the observed origin of the pulsation as deriving from motions within the inner parts of the core.

We model B68 as a Bonnor-Ebert sphere internally supported by thermal pressure and initially in pressure equilibrium with the external medium. The cloud is initially in critical equilibrium and stable against gravitational collapse. The initial conditions of the model cloud are listed in Table 3. We then follow the evolution of the cloud in two different scenarios. In the first case the external pressure increases by a factor of 4 and is held constant thereafter, and in the second case the pressure decreases by a factor of 4. The resultant hydrodynamics are treated one dimensionally for simplicity, and the density, velocity, pressure and temperature are calculated. To compare the model with observations, a molecular line radiative transfer code (Keto & Field 2005; Redman et al. 2004) is employed to calculate the spectral line profiles of HCO⁺ across the cloud assuming constant abundance of HCO⁺.

Sample results of the calculations are presented in Figure 7. The results show that the 1D cloud model can exhibit profiles that are either red or blue asymmetric depending on whether contraction or expansion is taking place. The HCO⁺ $J = 3 - 2$ spectral line profiles shape closely match our observed spectra and our model also predicts the profiles of the HCO⁺ $J = 1 - 0$ and HCO⁺ $J = 4 - 3$ lines. We make the firm prediction that observations of Barnard 68 taken in the HCO⁺ $J = 1 - 0$ line should reveal an identical asymmetry pattern as pronounced as that in the HCO⁺ $J = 3 - 2$ data presented here and that the HCO⁺ $J = 4 - 3$ line will be weak and single peaked. Calculations were also performed for the CS molecule and similar results (not shown here) obtain and match the CS $J = 2 - 1$ data of Lada et al. (2003).

The data show a mixture of red and blue asymmetric profiles simultaneously across the cloud rather than a single set of expanding or contracting motions but it seems reasonable that in a real cloud different portions of the cloud could be in different phases of the cycle. These higher order non-radial modes may be excited in the cloud by external pressure perturbations, similar to the mechanism envisaged by Lada et al. (2003) to explain their results. Keto et al (2006, in prep) have calculated the line profiles that would result from an analytic model of modes of oscillation and find that zones of expansion and contraction produce red and blue asymmetric spectra similar to those seen in B68.

It should soon be possible to attempt a fully 3D analysis of B68 in which the hydrodynamics, the dust continuum radiative transfer, chemistry and molecular line radiative transfer are all carried out self-consistently. Most of the ingredients are already avail-

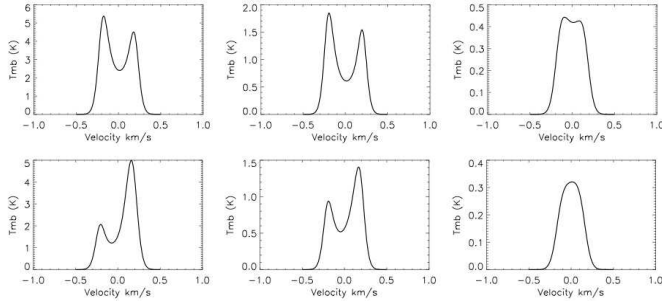


Figure 7. Model line profiles of HCO^+ for, from left to right, $J = 1 \rightarrow 0$, $J = 3 \rightarrow 2$ and $J = 4 \rightarrow 3$. The core is stable against overall gravitational collapse yet the pressure increase (upper panel) or decrease (lower panel) models exhibit asymmetric line profiles

able: a 3D hydrodynamic code could be combined with the 3D dust density distribution (recently constrained by J. Steinacker et al, in prep). Dark cloud chemistry models are available that are beginning to include freeze-out and the radiative transfer can be calculated in 3D with our code.

4 CONCLUSIONS

New observational data confirms that B68 exhibits split asymmetric molecular line profiles that indicate significant dynamical activity in the core. We favour a simple model in which the variety of spectral line profiles across the face of the cloud are the result of oscillatory motions about a state of gravitational equilibrium. The oscillations could have been started by a disturbance in the external pressure. A simple numerical hydrodynamic model in 1D that follows the evolution of an equilibrium Bonnor-Ebert sphere subject to a change in external pressure reproduces spectral line profiles similar to those observed. This simple model suggests that a more complex model that allowed for 3D oscillations could reproduce the variety of spectral line profiles across the face of the cloud.

At a very general level, this study re-inforces the need for caution, as emphasised by Rawlings & Yates (2001) and others, in the interpretation of line profiles observed along single lines of sight. A variety of dynamical activities, including rotation, non-spherical outflows and - as shown in this paper - pulsation, can mimic the characteristics of simple spherically symmetric inflow.

The depletion of molecular species observed toward the center of the cloud suggests that the cloud must have a lifetime long enough, a few million yr, to allow collisional processes to deplete the molecules from the gas phase by freeze-out onto grains. Turbulent models for the interstellar medium tend to indicate rapid star formation as localised dissipation of energy leads to stars ‘condensing’ out of molecular clouds. Typically in these models the star formation process is not traced beyond the formation of a Jeans mass worth of cloud because of resolution issues; the star is assumed to appear on a collapse timescale once a suitable prestellar core has formed. This process of density change is not necessarily one way. In another picture, slow mode MHD waves allow for the formation and then dissipation of density enhancements Falle & Hartquist (2002); Garrod et al. (2005). The chemistry of some molecular clouds appears to support this latter view in that the presence of several species is most plausibly explained if the cloud has undergone several such enhancements and contractions.

The combination of the oscillatory motions, an internal structure consistent with equilibrium, and a lifetime greater than several

crossing time suggests that long lived pressure supported clouds may exist in the turbulent ISM. Some part of the inefficiency of star formation may be due to formation of long-lived clouds. Many objects like B68 will promptly condense out of a turbulent medium, marking the endpoint of the supersonic turbulence cascade, but only a subset are destined to continue to collapse all the way to becoming a star. The rest will remain as stable starless cores eventually to be dissipated or triggered into collapse by external effects due to nearby massive stars and supernovae. The observational challenge is to identify those objects most likely to collapse with the difficulty, shown here, that some stable starless cores may exhibit strong evidence of dynamical activity yet, paradoxically, be perfectly stable against collapse.

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